

Comparative productivity of *Prosopis cineraria* and *Tecomella undulata* based agroforestry systems in degraded lands of Indian Desert

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Abstract: Tree-crop interactions were monitored by measuring tree growth characters of *Prosopis cineraria* L. and *Tecomella undulata* L. and yields of *Vigna radiata* (L.) in agroforestry systems in degraded lands of Indian Desert. Potential competition for resource between the trees and associated crop was analyzed by measuring soil water contents, soil organic matters and $\text{NH}_4\text{-N}$ at different depths of soil layers i.e., 0–25 cm, 25–50 cm and 50–75 cm in the experimental plots. The plots size were 16 m \times 18 m (D_1), 20 m \times 18 m (D_2) and 32 m \times 18 m (D_3) with tree densities of 208, 138 and 104 trees-ha⁻¹ after June 2002, respectively. Results showed that tree height increased by 3% to 7% during June 2002 to June 2004. Collar diameter increased by 30% and 11% in D_1 , 23% and 19% in D_2 and 18% and 36% in D_3 plots, respectively, in *P. cineraria* and *T. undulata* in two years period. The increase in crown diameter was 9% to 18% in *P. cineraria* and 11% to 16% in *T. undulata*. Tree growth was relatively greater in 2002 than in 2003. Yield of *V. radiata* increased linearly from D_1 to D_3 plots. Lowest soil water content at 1 m distance from tree base indicated greater utilization of soil water within the tree rooting zone. Concentrations of soil organic matters and $\text{NH}_4\text{-N}$ were the highest ($p < 0.05$) in 0–25 cm soil layer. *P. cineraria* was more beneficial than *T. undulata* in improving soil conditions and increasing crop yield by 11.1% and thus more suitable for its integration in agricultural land. The yield of agricultural crop increased when density of tree species was appropriate (i.e., optimum tree density), though it varied with tree size and depended upon resource availability. The result indicated bio-economic benefits of optimum density of *P. cineraria* and *T. undulata* over traditional practices of maintaining random trees in farming system in arid zones.

Keywords: arid region; crop yield; land productivity; soil water and nutrients; tree growth

Introduction

Water and nutrient availability are the limiting factors to growth and productivity of the vegetation in Indian arid region, and the situation becomes more adverse due to low and erratic rainfall (100 to 300 mm), high evaporation, temperature and wind speed and low water holding capacity of aridisol (NAPCD 2001). Currently agroforestry systems are recognized and become prevalent in the region for the ecological and socioeconomic benefits including products for household and national economics like food, fodder and medicine. The systems include agri-silviculture, agrosilvopastoral, multipurpose tree systems and agrihorticulture (Shankarnarayan et al. 1987). Trees integrated extensively in the crop and livestock production systems are *Prosopis cineraria*, *Tecomella undulata*, *Acacia nilotica*, *Acacia tortilis* and *Ailan-*

thus excelsa. Trees in agroforestry systems use water from soil that shallower plant roots cannot access (Dupraz 1999; Jose et al. 2000). Benefits of tree species depend on efficient and judicious management of soil and water resources (Joshi et al. 1989). Selection of appropriate combination of tree and crop species, adoption of appropriate spacing regime and suitable management practices (such as, trenching, pruning and thinning) are important aspects of field research.

In the Indian arid zone, *P. cineraria* and *T. undulata* are the most preferred tree species of agricultural land. *P. cineraria* enhances productivity of soil and the associated crops and provides fruit and leaf for vegetables and fodder, respectively (Mann and Saxena 1980; Abdel Bari et al. 2007). *T. undulata* is preferred for its high quality timber and medicinal values (Poffenberger et al. 1992). In order to study the effect of varying spacing regimes of *P. cineraria* and *T. undulata* and the soil plant interaction, an experiment was initiated in 1991 with 1 666, 833 and 417 stems per hectare for each species (Gupta et al. 1998). However, due to a decline in crop yield with advancing age, the experiment was further redesigned by reducing the tree density to 417, 278 and 208 stems-ha⁻¹ in June 1995 and to 208, 138 and 104 trees-ha⁻¹ in June 2002.

The objective of the study was to monitor tree-crop interactions in terms of tree growth, crop yield, soil water and changes in soil organic carbon for enhancing productivity of degraded drylands.

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Materials and methods

Site conditions

The experiment was initiated at the Arid Forest Research Institute, Jodhpur, where *P. cineraria* and *T. undulata* seedlings were planted at 2 m × 3 m spacing in July 1990. The mean annual rainfall of the plantation site is 350 mm (Singh and Rathod 2007). However, during cropping period (July to September) in 2002 and 2003 rainfall was 24.8 mm and 327.2 mm, respectively. Relative humidity (RH) in general is higher during monsoon (rainfall period, 66%, the average value from June to September), with a maximum RH of 98%. However, the maximum RH reached 93% in December 2002 and 95% in December 2003, with averages of 56% and 63% for the respective months. The maximum temperature rises to 48°C in the summer (May) and the minimum drops to 0°C (January) in the winter. Wind velocity in the summer months is 5.6 to 8.3 m·s⁻¹. The experimental farm is flat land with loamy sand soil (coarse loamy, mixed hyperthermic family of typic camborthids according to US soil taxonomy) underlain with a thick concretion of calcium carbonate at a depth of 75 cm. Soil had low contents of soil organic matter (0.32%), available P (11.4 mg·kg⁻¹), NO₃-N (4.81 mg·kg⁻¹) and NH₄-N (6.22 mg·kg⁻¹) and pH of 7.8. Soil moisture storage in the layer of 0–75 cm varies from 120 mm at 0.01 MPa to 35 mm at 1.5 MPa (Gupta et al. 1998).

Experimental design

The experiment was started in July 1991 by thinning the 1-year-old plantation at 2 m × 3 m spacing to maintain three different densities, i.e., 1 666 trees·ha⁻¹ at 2 m × 3 m spacing, 833 trees·ha⁻¹ at 4 m × 3 m spacing and 417 trees·ha⁻¹ at 4 m × 6 m spacing (Gupta et al. 1998). The plantation was thinned twice to obtain spacing of 4 m × 6 m, 4 m × 9 m and 8 m × 6 m in June 1995 and 8 m × 6 m, 8 m × 9 m and 8 m × 12 m in June 2002. Thus, tree densities were 417, 278 and 208 trees·ha⁻¹ during June 1995 to June 2002 and then reduced to 208, 138 and 104 trees·ha⁻¹ after June 2002. Plots size were 16 m × 18 m (D₁), 20 m × 18 m (D₂) and 32 m × 18 m (D₃) with tree densities of 208, 138 and 104 trees·ha⁻¹ after June 2002, respectively. The experiment was laid in randomized block design in three replications. After thinning in June 2002, there were six trees per plot in D₁ and D₃ and five trees per plot in D₂. Three control plots (size 15 m × 20 m) without trees were established 20 m away from the experimental plots. Since the objective of study was to see the effect of tree density on associated agricultural crop, sole tree plot as a control was not taken. Severe drought occurred in 2002; hence no crop sowing was done. *Vigna radiata* was sown in July 2003 and harvested in 2003 under rainfed. Mungbean (variety S-8) crop was sown at the seed rate of 15 kg·ha⁻¹.

Observations recording

Tree height, crown diameter (average of two perpendicular ob-

servations) and collar diameter (15 cm above the ground level) were recorded twice a year, before crop sowing (June) and after crop harvest (December). Grain and haulm yields of *V. radiata* were recorded after the harvest. Crop yield was recorded from sampling micro-plots of 1 m² area laid at 1 m and 2 m distances from the tree base as well as at the center of four trees (i.e., distance from tree base was 5 m in D₁, 6 m in D₂ and 7 m in D₃ plots). Soil water content was determined gravimetrically in the depth of 0–75 cm layer in the marked sample plots in September and December in 2002 and 2003. Soil samples were collected between 09:00 to 13:00 h at different depths i.e., 0–25 cm, 25–50 cm and 50–75 cm. Soil was dried at 110°C till constant weight for soil water content (SWC).

Chemical analyses of soil

Soil samples were collected from each micro-plot in December 2003. A single core was excavated to a depth of 0–75 cm and divided into 0–25 cm, 25–50 cm and 50–75 cm soil layers. The soil samples were mixed and homogenised to form a composite sample of each treatment and soil layer in three replicates. Soil samples were air dried and passed to a 2 mm mesh sieve and subjected to various analyses. Soil organic matter was determined by the partial oxidation method (Jackson 1973). NH₄-N was determined after 2 M KCl extraction using Tecator Model Enviroflow-5012 autoanalyser.

Statistical analysis

Data were statistically analyzed using SPSS statistical package version 8.0 for Windows 2000. Tree height and collar diameter were analyzed using a two-way ANOVA. Growth data were the dependent variables and tree species and tree densities were the fixed factors. The variations in crop yield due to tree species, distance from tree base and tree density were tested using a three way ANOVA model considering species, distance and tree density as the main factors. Since a single core soil sample divided into 0–25, 25–50 and 50–75 cm soil layers was collected for soil water content, soil organic matter and NH₄-N determination, it lacks randomization of soil layer and hence such data are highly correlated (Piepho et al. 2004). The data was analyzed using a repeated measure ANOVA with soil layer as a repetition factor (Dam et al. 2005). Percentage of soil water was square root transformed before statistical analysis (Sokal and Rolf 1981). To obtain the relations between crop yield and tree growth variables and soil water content, Pearson correlation coefficient was calculated. The least significant difference test was used to compare treatments at the *P* 0.05 levels. Relationship of crop yield (grain and grain + haulm, *Y*) with tree density was also worked out through regression equation.

Results

Tree growth

Tree height, crown diameter and collar girth of *P. cineraria* were significantly greater (*p*<0.01) than those of *T. undulata* (Table 1).

The effect of plant density on tree growth was significant ($p < 0.05$) in 2002 and 2004. At 14 years of age, trees were taller and thicker ($p < 0.01$) and had greater ($p < 0.05$) crown spread in D_3 plots compared with the D_1 and D_2 plots. Average increase in tree height, crown diameter and collar diameter was 17.2 cm, 23.7 cm and 2.5 cm during 2002–2003 and 8.5 cm, 16.9 cm and 0.5 cm during 2003–2004, respectively. The collar diameters were positively correlated with tree heights ($r = 0.667$, $p < 0.01$, $n = 54$) and soil water content (SWC) ($r = 0.401$, $p < 0.01$). Percentage of incremental increase in tree height over the data of June 2002 was 6.0% in D_1 to 7.0% in D_3 plots of *P. cineraria* and

30% in D_2 to 6% in D_3 plots of *T. undulata*. The corresponding increase in collar diameter was 18% in D_1 plots of *P. cineraria*. For *T. undulata*, the increase in collar diameter was 11% in D_1 to 36% in D_3 plots. The increase in crown diameter was 9% in D_1 to 18% in D_2 plots of *P. cineraria* and 16% in D_1 to 11% in D_3 plots of *T. undulata*. The increase was relatively greater in *T. undulata* than in *P. cineraria*, particularly during 2002–2003. Percentage of tree height increment during 2002–2003 was negatively related with SWC ($r = -0.437$, $p < 0.01$) in 25–50 cm soil layers.

Table 1. Growth of *Prosopis cineraria* and *Tecomella undulata* as influenced by spacing and the associated crops (by year) at Jodhpur, India

Species	Tree density (tree·ha ⁻¹)	Height (cm)			Collar diameter (cm)			Crown diameter (cm)		
		2002	2003	2004	2002	2003	2004	2002	2003	2004
<i>P. cineraria</i>	208 (D_1)	450 (9.1)	463 (7.6)	480 (12.6)	11.1 (0.45)	13.6 (0.38)	14.40 (0.44)	281 (16.8)	293 (17.7)	307 (14.7)
	138 (D_2)	497 (8.9)	513 (10.1)	528 (11.7)	14.3 (0.34)	16.5 (0.50)	17.6 (0.72)	302 (14.8)	326 (15.6)	356 (8.1)
	104 (D_3)	542 (9.9)	566 (12.1)	575 (12.6)	16.5 (0.35)	19.1 (0.42)	19.5 (0.43)	359 (9.8)	394 (14.8)	407 (13.6)
<i>T. undulata</i>	208 (D_1)	413 (7.2)	430 (11.5)	433 (13.1)	11.8 (0.32)	12.8 (0.21)	13.1 (0.27)	249 (16.6)	279 (16.6)	289 (12.3)
	138 (D_2)	449 (3.5)	459 (13.1)	462 (13.6)	12.8 (0.10)	15.1 (0.41)	15.2 (0.47)	298 (8.7)	319 (6.7)	338 (7.3)
	104 (D_3)	442 (4.1)	465 (11.5)	467 (8.8)	12.9 (0.13)	17.2 (0.32)	17.5 (0.38)	335 (2.9)	356 (7.5)	372 (8.8)
F value of two way ANOVA										
Species		267.6**	47.5**	55.5**	34.6**	18.7**	24.5**	3.89NS	3.06NS	6.67*
Density		49.0**	4.8*	3.4NS	57.1**	83.8**	50.4**	21.19**	20.75**	33.25**
Species X density		3.23NS	19.3**	14.1**	24.0**	1.0NS	0.7NS	0.62NS	0.73NS	0.40NS

*, significant at $p < 0.05$, **, significant at $p < 0.01$ and NS, not-significant ($p > 0.05$). Values are means of three replicate plots with SE in parentheses.

Population and production of *V. radiata*

Population density (number·m⁻²) of *V. radiata* seedlings in the control plots was 34.67 ± 0.33 (mean \pm 1 SE) m⁻² and negatively correlated ($r = 0.293$, $p < 0.05$) with tree density. As compared to the control plots, the population density reduced to 17.81 seed-

lings per square meter (Tables 2) in the tree-integrated plots in spite the similar seed rate. The reduction in population density was less in *P. cineraria* than in *T. undulata* plots. The population density decreased from 44.2% to 56.7% in D_1 , 50.0% to 68.3% in D_2 and 49.1% to 63.5% in D_3 plots of *P. cineraria*, and 38.5% to 50.0% in D_1 , 43.3% to 56.7% in D_2 and 41.3% to 54.8% in D_3 plots of *T. undulata* plots (Table 2).

Table 2. Average yield of *Vigna radiata* influenced by spacing and associated tree species at Jodhpur, India

Species	Tree density (tree·ha ⁻¹)	Population density of <i>V. radiata</i> seedling (no·m ⁻²)				Grain yield (t·ha ⁻¹)				Haulm yield (t·ha ⁻¹)			
		1 m	2 m	Centre	Mean	1 m	2 m	Centre	Mean	1 m	2 m	Centre	Mean
Control	no tree	-	-	-	34.67±0.33	-	-	-	1.616	-	-	-	4.539
<i>P. cineraria</i>	208 (D ₁)	15.33 (0.33)	17.00 (0.58)	19.66 (0.88)	17.33	0.223 (0.014)	0.420 (0.034)	0.720 (0.019)	0.454	1.949 (0.053)	2.068 (0.100)	2.580 (0.312)	2.199
	138 (D ₂)	17.33 (0.33)	20.33 (0.88)	23.67 (1.33)	20.44	0.498 (0.076)	0.720 (0.019)	0.803 (0.097)	0.674	2.591 (0.338)	2.403 (0.386)	3.840 (0.860)	2.945
	104 (D ₃)	17.00 (0.58)	19.33 (0.88)	22.00 (2.08)	19.44	0.817 (0.027)	1.210 (0.040)	1.860 (0.054)	1.296	2.632 (0.264)	2.307 (0.046)	3.057 (0.316)	2.665
<i>T. undulata</i>	208 (D ₁)	13.33 (0.33)	15.33 (0.33)	17.33 (1.20)	15.33	0.210 (0.009)	0.375 (0.038)	0.680 (0.025)	0.422	1.745 (0.058)	1.927 (0.019)	2.397 (0.137)	2.023
	138 (D ₂)	15.00 (0.58)	17.67 (0.88)	20.33 (0.33)	17.67	0.470 (0.075)	0.686 (0.021)	0.752 (0.066)	0.636	2.137 (0.217)	2.380 (0.327)	2.770 (0.147)	2.427
	104 (D ₃)	14.33 (0.88)	16.67 (0.88)	19.00 (0.58)	16.67	0.752 (0.012)	1.191 (0.059)	1.703 (0.089)	1.215	2.330 (0.307)	2.315 (0.078)	2.833 (0.087)	2.493
Two way ANOVA result				<i>F</i> -value	<i>p</i> -value	<i>F</i> -value		<i>p</i> -value	<i>F</i> -value		<i>p</i> -value		
Species				36.409	<0.001	4.467		<0.05	4.224		<0.05		
Density				14.512	<0.001	418.2		<0.001	6.367		<0.01		
Distance				46.827	<0.001	204.2		<0.001	10.489		<0.001		
Density x distance				0.457	NS	27.43		<0.001	0.493		ns		

p values are results of a two-way ANOVA for mean yields. Seedling population, grain yield and haulm yield in the control plot were 34.67 ± 0.33 numbers, 1.616 ± 0.045 t·ha⁻¹ and 4.110 ± 0.292 t·ha⁻¹, respectively. Values are means of three replicate plots with SE in parentheses. Ns, non-significant at $p = 0.05$ level

Grain and haulm yields of *V. radiata* in the control plots were 1.62 and 4.54 t·ha⁻¹, respectively. However, the yields in tree-integrated plots were reduced by 51.5% in grain and 45.8% in haulm. The reductions in the grain and haulm yields were relatively greater in *T. undulata* plots than in the *P. cineraria* plots. In the tree-integrated plots, grain yield was the highest ($p < 0.05$) in D₃ and the lowest in D₁ plots (Table 2). Haulm yield was also the highest in D₃ plots ($p < 0.01$). The yields of *V. radiata* increased ($p < 0.05$) with increasing distance from tree base, and the highest yields occurred in the center micro-plots, significantly higher than that at 1 m and 2 m distances micro-plots. In center of four trees, the grain and haulm yields reduced in all the three density treatments except in the central micro-plots in D₃ density plots, where grain yield increased by 15% in *P. cineraria* and 5.4% in *T. undulata* plots compared with the control plots. The crop yield was related negatively with tree density ($r = -0.586$, $p < 0.01$) and positively with tree height ($r = 0.340$, $p < 0.05$), collar girth ($r = 0.647$, $p < 0.01$), *V. radiata* density ($r = 0.687$, $p < 0.01$) and SWC ($r = 0.264$, $p = 0.053$). Yield of *V. radiata* grain was inversely related (i.e., $\ln(Y) = a + (b_0/D)$; $R^2 = 0.5906$, SE = 0.3845, $a = 2.5288$, $b_0 = 230.9220$, $F = 75.027$, $p < 0.001$) with tree density. Whereas total crop yield showed a quadratic fitting (i.e., $Y = a + b_0 \cdot D + b_1 \cdot D^2$; $R^2 = 0.3477$, SE = 74.6328, $F = 13.595$, $p < 0.001$) with tree density. Where Y is the crop yield (grain + haulm), D is tree density (trees·ha⁻¹) and a , b_0 and b_1 are regression constant with value of 578.7769, -2.1984 and 0.0031, respectively in quadratic fitting. The yield increased linearly with decrease in tree density, though the yield was even lesser at a tree density of 104 trees·ha⁻¹ (3.838 t·ha⁻¹) than in the control (6.155 t·ha⁻¹) plots.

Soil water content

Repeated measure ANOVA indicated significantly ($p > 0.01$) low soil water content (SWC) in top 0–25 cm soil layer in all four observations recorded in September and December of 2002 and 2003. SWC increased ($p < 0.05$) in deeper soil layers (Fig. 1). SWC was lesser ($p < 0.05$) in 2002 than in 2003. SWC was greater ($p < 0.05$) in *P. cineraria* than in *T. undulata* in December both the years ($p = 0.073$). SWC was negatively correlated ($r = -0.581$, $p < 0.001$) with tree density. SWC was lowest ($p > 0.05$) in D₁ plots in most of the observations. However, in September 2002, SWC was the lowest in 0–25 cm soil layer in D₃ plots. Distance from tree base indicated that SWC was the highest ($p < 0.05$) at centre micro-plots and the lowest at 1 m distance in all soil layers and months.

Soil organic matter and NH₄-N

There was an increase in SWC by 1.6–1.8 fold in *P. cineraria* and 1–2 fold in *T. undulata* in 0–25 cm soil layer in December 2002 as compared to SWC in September 2002 (Fig. 1b and 1f). However, there was a decrease in SWC in *P. cineraria* and *T. undulata* plots by 64% and 67%, respectively, in 0–25 cm soil layer in December 2003 than in September 2003 (Fig. 1d and 1h).

In 25–50 cm soil layer, the decrease in SWC of the *P. cineraria* and *T. undulata* plots was by 56% and 55% in 2002 and by 48% and 52% in 2003, respectively. The reduction in SWC of *P. cineraria* and *T. undulata* plots in 50–75 cm soil layer was by 62% and 67% in 2002 and by 30% and 35% in 2003, respectively.

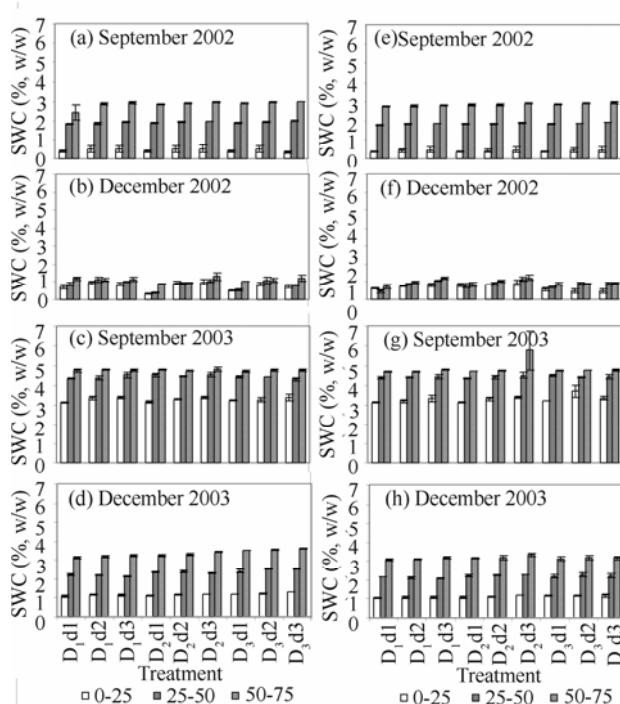


Fig. 1 Soil water content (% w/w) as influenced by spacing of *Propolis cineraria* and *T. undulata* trees, associated crops and distance from tree base. Values are means of three replicate plots. Error bars are ± 1 SE. Left panels are *P. cineraria* and right panels are *T. undulata*. Tree densities are 208 trees·ha⁻¹ (D₁), 138 trees·ha⁻¹ (D₂) and 104 trees·ha⁻¹ (D₃). Distance from tree base is 1 m (d1), 2 m (d2) and centre of four trees (d3)

Average content of soil organic matter (SOM) was 0.24% (0.37%, 0.23% and 0.12% in 0–25, 25–50 and 50–75 cm soil layer, respectively) in the control plots. Tree-integrated plots had an average SOM of 0.19%, being the highest in the 0–25 cm soil layer and decreased ($p < 0.05$) in the deeper soil layers. Average SOM was 0.201% ($p < 0.05$) in *P. cineraria* and 0.185% in *T. undulata* plots. SOM was lower ($p < 0.05$) in the D₁ than in the D₂ and D₃ plots. SOM was greater ($p < 0.05$) in D₃ plots in 50–75 cm soil layer (Fig. 2a & 2b) than in the other density plots in same soil layer. While considering the distances, SOM was the highest ($p < 0.05$) at 1 m distance in 0–25 and 50–75 cm soil layers and at 2 m in 25–50 cm soil layer. SOM had a negative ($r = -0.601$, $p < 0.01$) relation with tree density and positive ($r = 0.407$, $p < 0.01$) relation with SWC in December 2003.

Averaged NH₄-N concentration in 0–75 cm soil layer was 3.39 mg·kg⁻¹ (4.54, 3.50 and 2.13 mg·kg⁻¹ in 0–25, 25–50 and 50–75 cm soil layers, respectively) in the control plots. Averaged NH₄-N concentration in tree-integrated plots was lower than that of

the control plots. $\text{NH}_4\text{-N}$ concentration in tree-integrated plots was the highest ($p<0.05$) in 0–25 cm soil layer and decreased ($p<0.05$) in the deeper soil layers. $\text{NH}_4\text{-N}$ concentration was greater ($p<0.05$) in *P. cineraria* ($3.30 \text{ mg}\cdot\text{kg}^{-1}$) than in *T. undulata* ($3.03 \text{ mg}\cdot\text{kg}^{-1}$) plots (Fig. 2c and 2d). The concentration of $\text{NH}_4\text{-N}$ was lowest ($p<0.05$) in D_1 plots. Highest and lowest concentration of $\text{NH}_4\text{-N}$ was at 1 m and 2 m distance in 0–25 cm soil layer, at 2 m and centre in 25–50 cm soil layer and at centre and 2 m distances in 50–75 cm soil layer, respectively. $\text{NH}_4\text{-N}$ concentration had negative relation ($r = -0.488$, $p<0.01$) with tree density and positive relations with SWC ($r = 0.691$, $p<0.01$), *V. radiata* population ($r = 0.400$, $p<0.01$) and crop yield ($r = 0.313$, $p<0.05$).

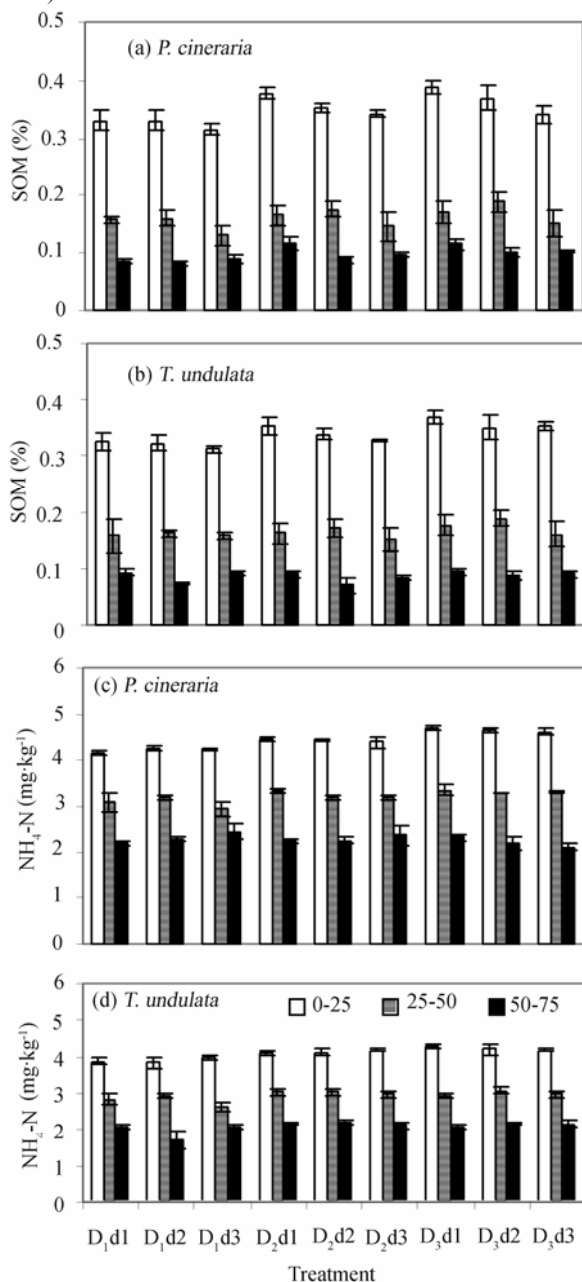


Fig. 2 Concentration of soil organic matter and ammonical nitrogen influenced by density of *Prosopis cineraria* and *T. undulata* trees, associated *V. radiata* crop and distance from tree base. Values are

means of three replicate plots. Error bars are +1SE. Tree densities are 208 trees·ha⁻¹ (D₁), 138 trees·ha⁻¹ (D₂) and 104 trees·ha⁻¹ (D₃). Distance from tree base are 1 m (d₁), 2 m (d₂) and centre of four trees (d₃)

Discussions

Tree growth

Trees and associated crop have a high level of competition for growth resources like light, water and nutrients affecting the productivity of an agroforestry system (Belsky et al. 1993). Variation in tree growth over time in both the tree species was due to variability in size of the trees at the start of the experiment in June 2002, species character, tree density and agriculture crop (Table 1). Taller and thicker trees with greater crown spread in the D₃ plots were probably due to more space compared with other plots, which could utilize greater soil water for height ($r = -0.298$, $p<0.05$) and collar girth ($r = -0.356$, $p<0.01$) growth. But trees in D₁ plots had greater incremental growth as compared with those in D₂ and D₃ plots probably due to the increased spacing after thinning in June 2002. Greater increment (15 to 25%) in collar diameter of *P. cineraria* and *T. undulata* in D₂ than in D₁ and D₃ plots was believed to be due to higher utilization of soil resources. This was evidenced by a negative correlation ($r = -0.437$, $p<0.01$) of percentage of height increment in 2002–2003 with SWC in December 2002. The trees in 2002–2003 with 71.5 mm rainfall had comparatively greater growth increment than that of *V. radiata* intercropped in 2003–04 with 392.0 mm rainfall. This suggests that a competitive use of soil resources by *V. radiata* affect tree growth.

Crop yield

Population density and grain and haulm yields of *V. radiata* in tree-integrated plots were reduced by about 50% as compared to the control plots due to a high-level competition by trees (Table 2). Greater yield of *V. radiata* in the *P. cineraria* plots than in the *T. undulata* plots is attributed to higher availability of soil water ($r = 0.264$, $p = 0.053$), organic matter ($r = 0.272$, $p<0.05$) and N availability ($r = 0.313$, $p<0.05$, $\text{NH}_4\text{-N}$), which is similar to the observations of Aggarwal and Kumar (1990). Reduction in the crop yield was relatively greater ($p<0.01$) in D₁ and D₂ plots than in D₃ and control plots, indicating greater intensity of competition between trees and crop. This suggests that a population density of >138 trees·ha⁻¹ had a depressive impact on *V. radiata* crop. Trees and associated crop had a high level of competition for growth resources as indicated by low SWC near root zone of trees (Fig. 1). Low rainfall during peak growing phase (August) of *V. radiata* possibly enhanced the intensity of competition and therefore reduced the crop yield. Reduction in the crop yield in D₃ plots suggested that competition between trees and associated crop for resources prevailed in D₃ plots. Competitive use of soil resources reduced soil water and crop yield near tree roots particularly at 1 m and 2 m distance from trees as compared to that at the centre of four trees. But non-significant ($p>0.05$) difference in grain yield in the control and the central micro-plots in D₃ density plots showed adequate availability of soil resources

and/or reduced competition by trees for resource use (Fig. 1).

Soil water resource

Drought decreased soil water availability in the upper soil layers in the September 2002; thus the existing vegetation for survival can only absorb water from the deeper soil layers. Greater use of deeper soil water was demonstrated by a decrease in SWC by 56% and 65% in 25–50 cm and 50–75 cm soil layer in December 2002 as compared with those in September 2002. However, about 2-fold increase in SWC in 0–25 cm soil layer in December than in September 2002 was probably due to absorption of atmospheric water and/ or dew deposition on soil surface (Fig. 1b and 1f), which was similar to the observation of Ninari and Berliner (2004). Despite of average relative humidity of about 56% in December, extremely dry soil probably caused water vapor absorption (Scanlon and Milly 1994) increasing SWC in the upper soil layer. However, there was a positive relation between soil water increase and tree height ($r = 0.445$, $p < 0.01$) and collar girth ($r = 0.561$, $p < 0.01$). This indicated that tree root absorption on soil water influenced redistribution of water in upper soil layer after withdrawal of water from deeper soil layers (i.e., greater decrease in SWC in 25–50 cm and 50–75 cm soil layers, Fig. 1b & 1f) and/ or absorption of atmospheric water (Lalley and Viles, 2006).

Lower SWC in the *T. undulata* than in the *P. cineraria* plots was possibly due to either greater use of soil water by *T. undulata* than the *P. cineraria* trees, and/ or greater evaporation losses in *T. undulata* plots particularly in upper soil layer. However, greater SWC in D₂ (at centre) and D₃ plots of *T. undulata* in September 2003 indicated that the water requirement of this species was fulfilled by an adequate water supply through rainfall (Fig. 1). Though a low intensity of regular rainfall enhanced water availability, but simultaneous increase in competition reduced crop yield in the tree-integrated plots. Low soil water near root zone of the trees indicated greater utilization of soil water by tree roots. Livesley et al. (2005) also observed an increase in soil water with increase in distance from *Grevillea robusta* row in *Grevillea robusta*-maize system. However, SWC reductions in *P. cineraria* and *T. undulata* plots were by 64% and 67% in 0–25 cm, 48% and 52% in 25–50 cm, and 30% and 35% in 50–75 cm soil layer between September and December 2003, respectively. This indicated relatively greater soil water use by both tree and crop from upper soil layer affecting crop yield.

Soil organic matter and NH₄-N

High population of *V. radiata* can result in great return of the organic matter and the nutrients through litter/root decomposition and mineralization and thus enhance higher soil organic matter (SOM) and NH₄-N in the control plots than in the tree integrated plots. Singh et al. (2000) observed an increase in soil organic matter in consonance with the period of litter production and crop. The amount of SOM and NH₄-N was the highest in the 0–25 cm soil layer and decreased ($p < 0.05$) in the deeper soil layers (Fig. 2), indi-

cating greater turn over of litters and root in top soil layer. Distribution of SOM in soil layers had a slightly stronger association with tree than with climate, where an increase in SOM near tree roots in the deeper soil layers was similar to the observations of Jobbágy and Jackson (2000). This was shown by relatively greater ($p < 0.05$) amount of SOM in *P. cineraria* (0.201%) than in *T. undulata* plots (0.185%) and was related to trees height and collar girth (Table 1). Jiménez et al. (2007) observed variations in SOC under *Vochysia guatemalensis*, *Calophyllum brasiliense*, *Stryphnodendron excelsum* and *Hieronyma alchorneoides* with average soil organic carbon concentration of 44.9 g·kg⁻¹ to 55.2 g·kg⁻¹ in 0–10 cm soil layers and 12.7–16.8 g·kg⁻¹ in 40–50 cm soil layers. Increase ($P < 0.05$) in SOM from D₁ to D₃ plots suggested that SOM increased with tree size and age. This was also demonstrated by greater amount of SOM at 1 m than at 2 m and centre micro-plots (Fig. 2a and 2b). Significantly greater ($p < 0.05$) SOM in 50–75 cm soil layer in D₃ plots than in the other density plots was possibly due to deep penetration of the roots and root decomposition to turn into organic matter. Elberling et al. (2003) recorded greater soil carbon (4.4 kg·m⁻²) in open woodland than to 2.7 kg·m⁻² in grassland in semi-arid savanna in Senegal. Greater ($p < 0.05$) N availability in *P. cineraria* than in the *T. undulata* plots was due to nitrogen rich litter of *P. cineraria*. However, lower ($p < 0.05$) availability of NH₄-N in the D₁ plots than in the D₂ and D₃ plots was possible caused by low quantity of litter addition by smaller trees and low population of *V. radiata*. This conclusion can be indicated by a positive correlation of NH₄-N concentration with tree size ($r = 0.400$, $p < 0.01$) and population of *V. radiata* (Table 2 and Fig. 2c & 2d). However, relatively greater amount of NH₄-N in the control than in the tree-integrated plots suggests the role of *V. radiata* in enhancing NH₄-N concentration through biological nitrogen fixation.

Conclusions

The study suggests that *P. cineraria* and *T. undulata* maintained at optimum tree densities can enhance productivity of associated agricultural crops by improving soil water, soil organic matter and N availability. Trees maintained productivity of crop or tree-self even during drought and provided beneficial effects on crop by improving soil water in upper soil layer and by redistributing the water withdrawn from deeper soil layers. However, tree size, competition for resources at high densities and soil water deficit resulted from increased solar radiation at low tree density were the probable factors affecting crop yield. Low rainfall in crop growth phase enhanced competitive effect between trees and the crop, and resulted in a reduce in the yield of *V. radiata*. However, about 11.1% greater crop yield in *P. cineraria* than in *T. undulata* plots indicated greater benefits of *P. cineraria* under tree integration. Thus, farmers can improve agricultural production by integrating these tree species at optimum tree density, which maintain land productivity by enrichment of soil nutrients. The result indicated bio-economic benefits of optimum tree density of *P. cineraria* and *T. undulata* for their optimum utilization over traditional practices of rarefying and tending of trees in farming system in arid zones.

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